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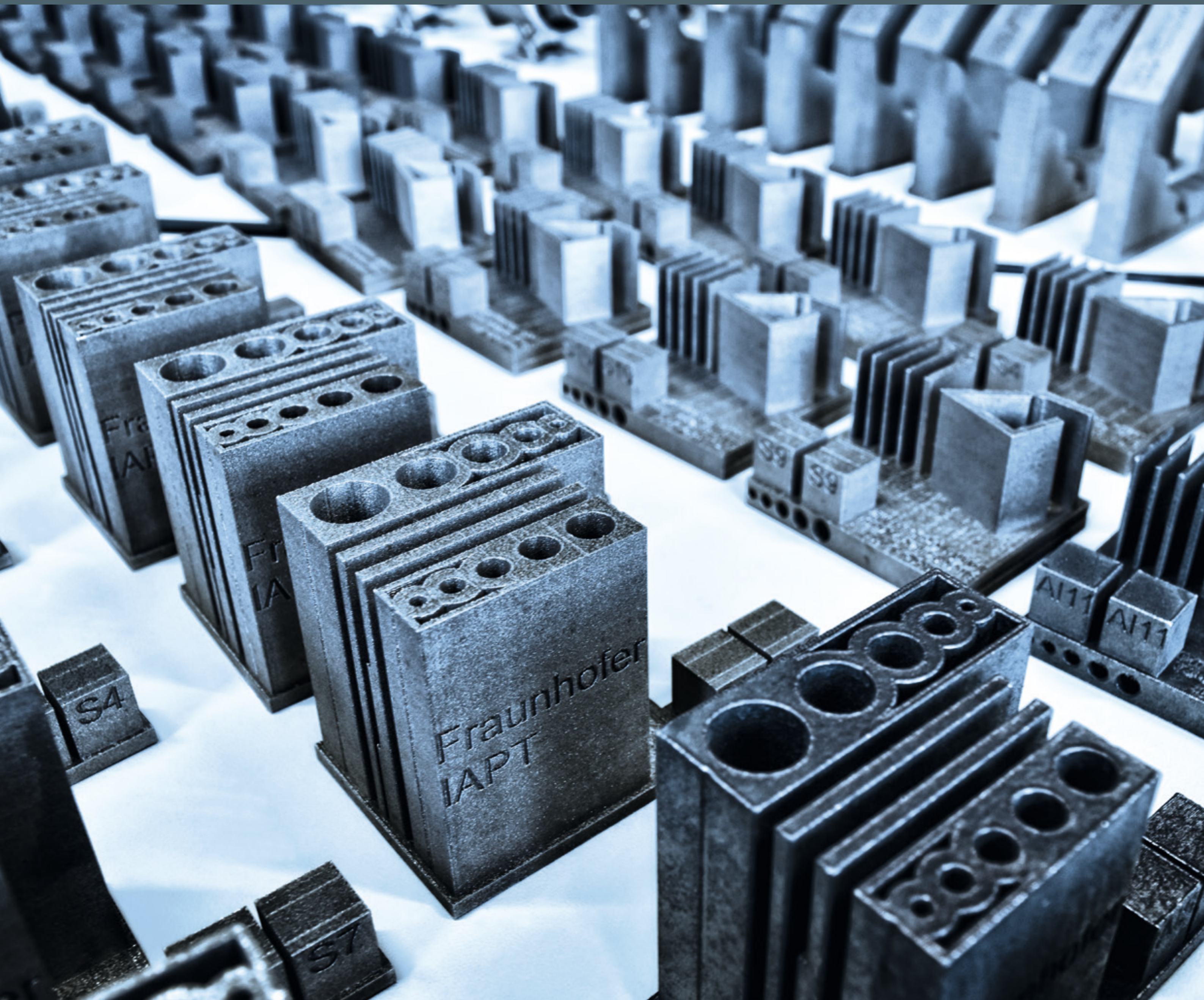
FRAUNHOFER RESEARCH INSTITUTION FOR ADDITIVE MANUFACTURING TECHNOLOGIES IAPT

ADDITIVE MANUFACTURING SURFACE FINISHING STUDY

BENCHMARK OF SURFACE FINISHING PROCESSES FOR METAL AM COMPONENTS



CONTENT

1_MOTIVATION

Insights to be gained:

- What surface properties can be achieved with which post-processing method
- What are strengths and limitations of the most market relevant post-processing methods
- How suitable are the post-processing methods for different AM materials
- What are price ranges of the post-processing methods and their major cost drivers

Additive Manufacturing of metals is paving its way to a fully established industrial manufacturing technology. This is due to the design freedom and economically viable production of small lot sizes. Meanwhile, Additive Manufacturing is used across all industries from automotive to aerospace and from medical to mechanical engineering.

However, a current challenge that industry is facing concerning additively manufactured parts is the surface quality. Resistance to fatigue failure and optimum flowability of fluids are just some industrial requirements that demand high surface quality. In many cases, the surface quality of parts manufactured with Laser Powder Bed Fusion cannot serve those requirements. For this reason, post-processing is essential in order to improve the part's surface quality. These post-processing processes focusing on the finishing of surfaces are in the field of tension between surface quality, costs and ablation rate, which can negatively affect the geometric properties of the part. In addition, high quality surfaces are often required in internal structures of a part as well, which imposes high demands on the surface finishing process.

The aim of this study is to give an overview of industry-related surface finishing processes that are most relevant for additively manufactured metal parts and to compare them with each other based on benchmark criteria. This will help to decide which processes are most suitable for a specific application.

2_ABOUT FRAUNHOFER IAPT

Fraunhofer IAPT is one of the leading research institutes in the field of Additive Manufacturing (AM). We specialize in the following areas: design, process technology, factory systems, digitalization and qualification.

Our objective is to scale up additive processes and technologies and facilitate their transfer to industry, thereby enabling the manufacture of completely new and resource-efficient products.

We can provide you with customized solutions and help launch you as a competitive player in the field of Additive Manufacturing.

More information can be found here:
www.iapt.fraunhofer.de

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3_ABOUT THE AUTHORS

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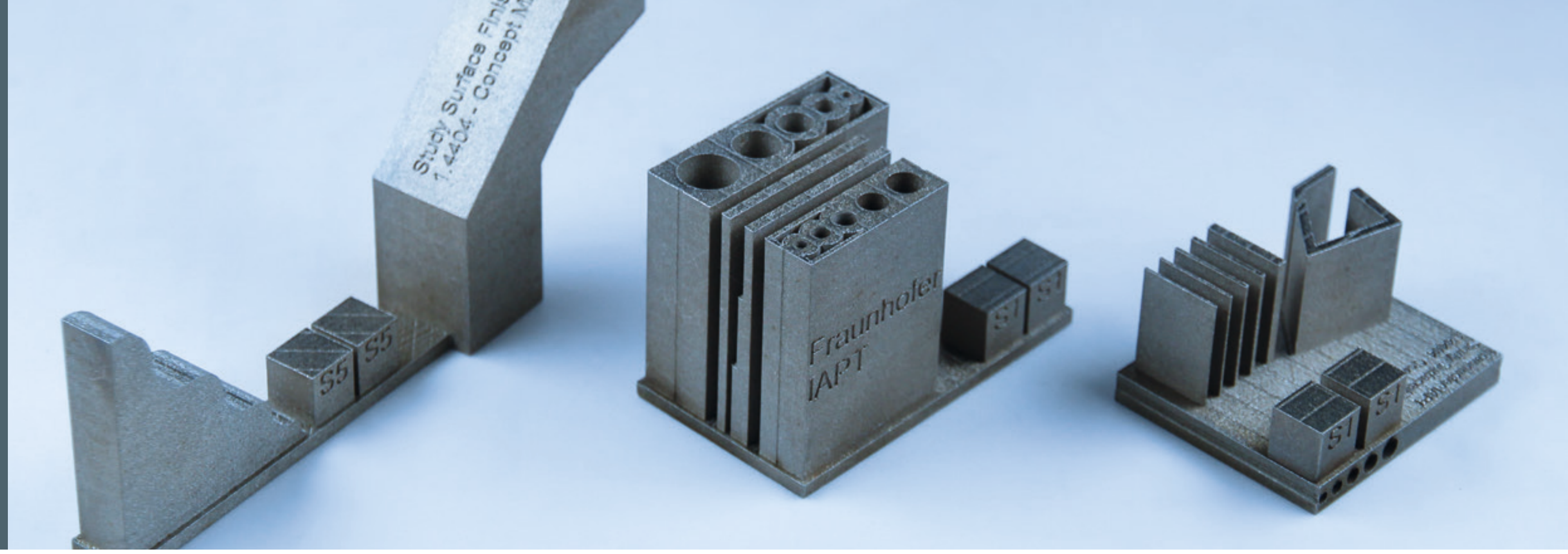
4_APPROACH OF THE STUDY



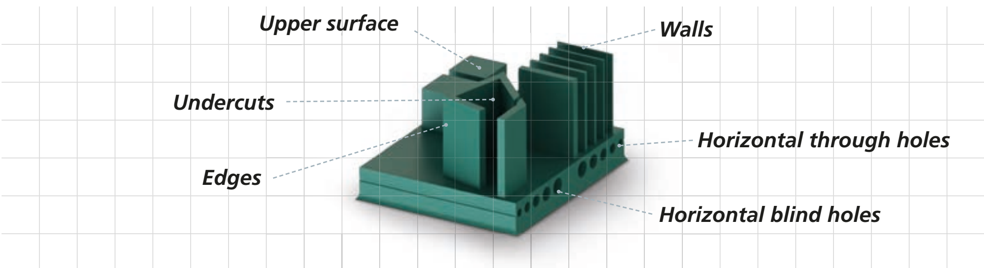
4.1_TEST SPECIMENS

The test specimens were designed with regard to a developed list of industrial requirements in order to investigate the effectiveness of various surface finishing processes. The list of requirements contains common industrial demands such as supported or unsupported surfaces built with different building angles, erosion rate, edge rounding and penetration depth. In addition, the readability of lettering and the hardness of the material is investigated. For each requirement an appropriate geometry was taking into account the measurability after processing. Furthermore, the Fraunhofer IAPT design guidelines for AM design were considered. For handling purposes, the geometries were grouped into three test specimens. Reference cubes were added to each test specimen to monitor differences in surface finishing between the three test specimens of one set.

Overview of the benchmark criteria and the corresponding geometric features

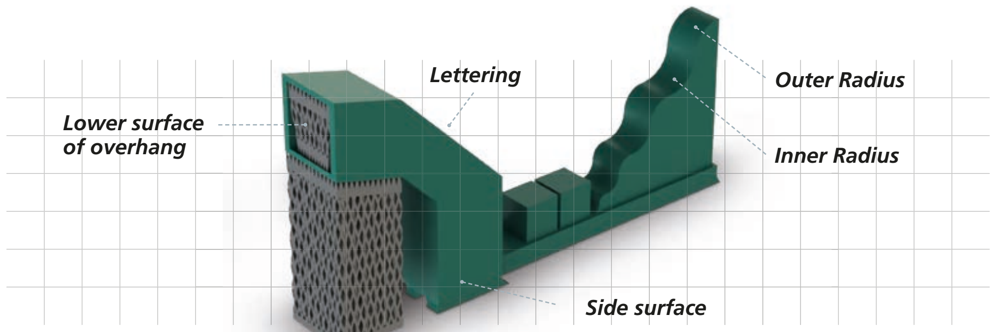
- Surface roughness: upper surface, side surface, lower surface of overhang, horizontal holes, vertical holes, undercut, lengthways gap
- Surface hardness: upper surface
- Erosion rate: wall, lettering, inner radius, outer radius
- Edge rounding: inner edge, outer edge
- Penetration depth: horizontal drilling, vertical drilling, lengthways gap

Test specimen A (50 x 42 x 28 mm) consists of horizontal printed holes with different diameters to investigate the penetration depth of the surface finishing processes and the achieved surface roughness. Vertical printed walls with different thickness and undercuts with different angles are present to evaluate the erosion rate and edge rounding of the investigated surface finishing processes.



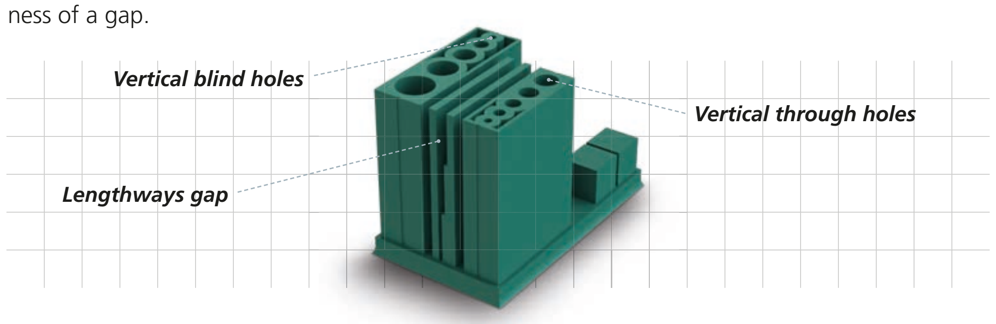
Test specimen A

Test specimen B (125 x 20 x 65 mm) is designed to investigate the surface roughness of supported and unsupported surfaces built with different building angles. For this purpose, a geometry with three hollow sections is used. The support structures are removed before surface finishing. Measurements of the outer and inner surface of the hollow structure provide a broad spectrum of various surface qualities and processing conditions. In addition, the erosion rate and dimensional accuracy of different convex and concave radii are evaluated. The lettering is used to rate the readability after the surface finishing has been processed.



Test specimen B with support structure

Test specimen C (67 x 38 x 47 mm) includes vertical printed holes with different diameters to study the penetration depth of the surface finishing process and surface roughness. Larger diameters are used compared to the horizontal holes of test specimen A which is constrained by design restrictions. Holes with equal diameters can be used for comparison of the surface finishing of vertical and horizontal holes. A wall with stepwise decreasing thickness in combination with a straight wall is used to investigate penetration depth and resulting surface roughness of a gap.

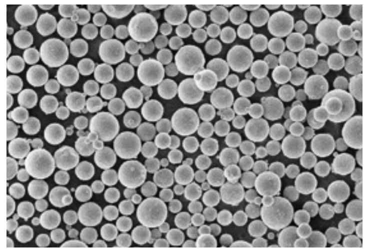


Test specimen C

The reference cubes on each test specimen are used to measure surface roughness and hardness of the specimen.

4.2_INVESTIGATED MATERIALS

Alloys from the three material groups 'titanium alloys', 'aluminum alloys' and 'stainless steels' are investigated in this study, since they are most relevant for Metal AM. For each of these groups the most commonly used alloy in regards to Laser Powder Bed Fusion was selected. For the manufacturing of the test specimen, recycled powder was used, which is sieved after each build-job, as it is common practice. From time to time virgin powder was added to replace removed powder. To ensure the powder quality of the recycled powder Fraunhofer IAPT analyzed the particle size distributions and particle shapes for this study.

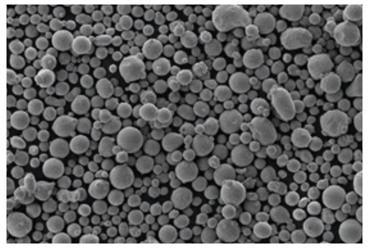


Scanning electron micrograph (SEM) images of Ti6Al4V with 500x magnification

Titanium Alloy Ti6Al4V

Titanium alloys are lightweight, have a high specific strength, are thermal and corrosion resistant as well as biocompatible. Because of these characteristics titanium alloy parts are broadly used in the industry for high performance applications (e.g. for aerospace or medical parts). In general, the machinability is rather challenging, which often leads to high machining costs and long lead times in conventional processing. Because of that, many business cases exist for the Additive Manufacturing of titanium alloy parts that offer substantial cost advantages. In regards to Laser Powder Bed Fusion, Ti6Al4V today is widely used for commercial fabrication, so it was chosen as one of the three investigated materials.

The manufacturer of the Ti6Al4V powder, which was chosen to build the specimens, gives a particle size range from 20 µm (D10) to 53 µm (D90) and a chemical composition in accordance with the ASTM B348 Grade 23 and ASTM F3001 standards.



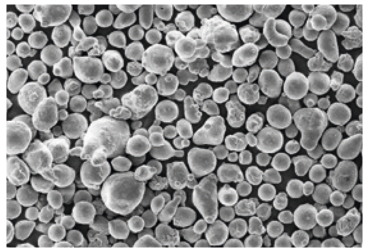
Scanning electron micrograph (SEM) images of 1.4404 with 500x magnification

Stainless Steel 1.4404

Stainless steel exhibits several favorable mechanical properties such as high tensile strength, high ductility and hardness in combination with a high corrosion resistance. Those properties make stainless steel the perfect material for a vast field of applications, like e.g. machine components, ductwork, tools, medical instruments or food-safe applications. For this study, 316L, respectively 1.4404, was selected due to its widespread use for Additive Manufacturing parts in the industry.

The chemical composition of the 1.4404 powder met the typical standards, and the manufacturer gives a particle size range from 20 µm (D10) to 45 µm (D90).

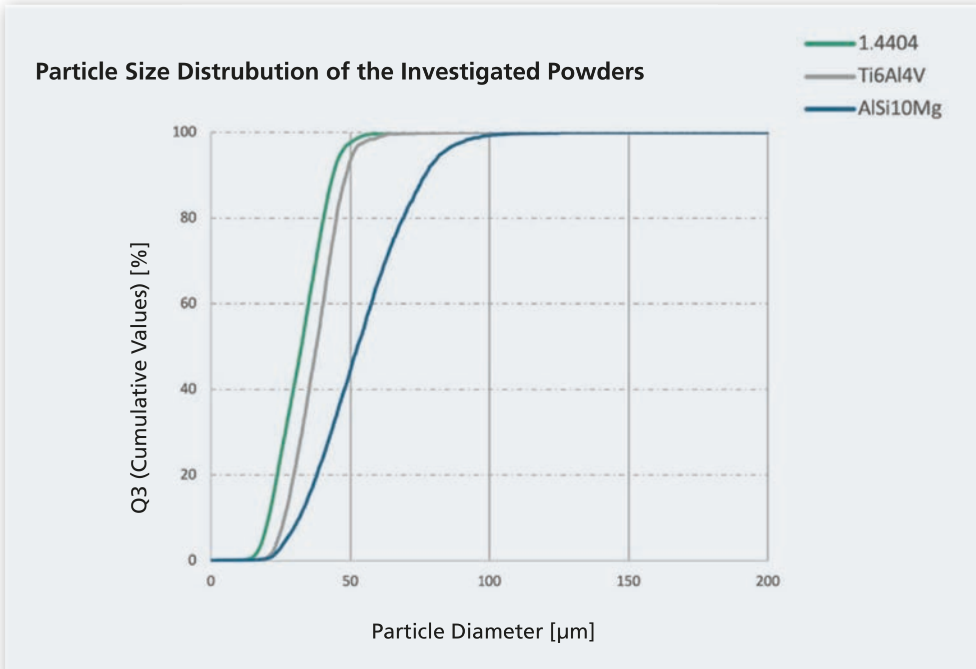
Aluminum Alloy AlSi10Mg



Scanning electron micrograph (SEM) images of AlSi10Mg with 500x magnification

In general, aluminum alloys are lightweight, suitable for casting and easy to process. They are broadly used in automotive and aerospace applications, especially because of the lightweight aspect in combination with a relatively low production cost. Concerning its superior machinability, the processing of aluminum Additive Manufacturing parts is often of lower commercial advantage. For Laser Powder Bed Fusion AlSi10Mg is to date by far the dominant alloy for aluminum parts and was therefore selected for this study.

The manufacturer of the AlSi10Mg powder gives a particle size range from 20 µm (D10) to 63 µm (D90) and the chemical composition is in conformance with EN AC-43000.

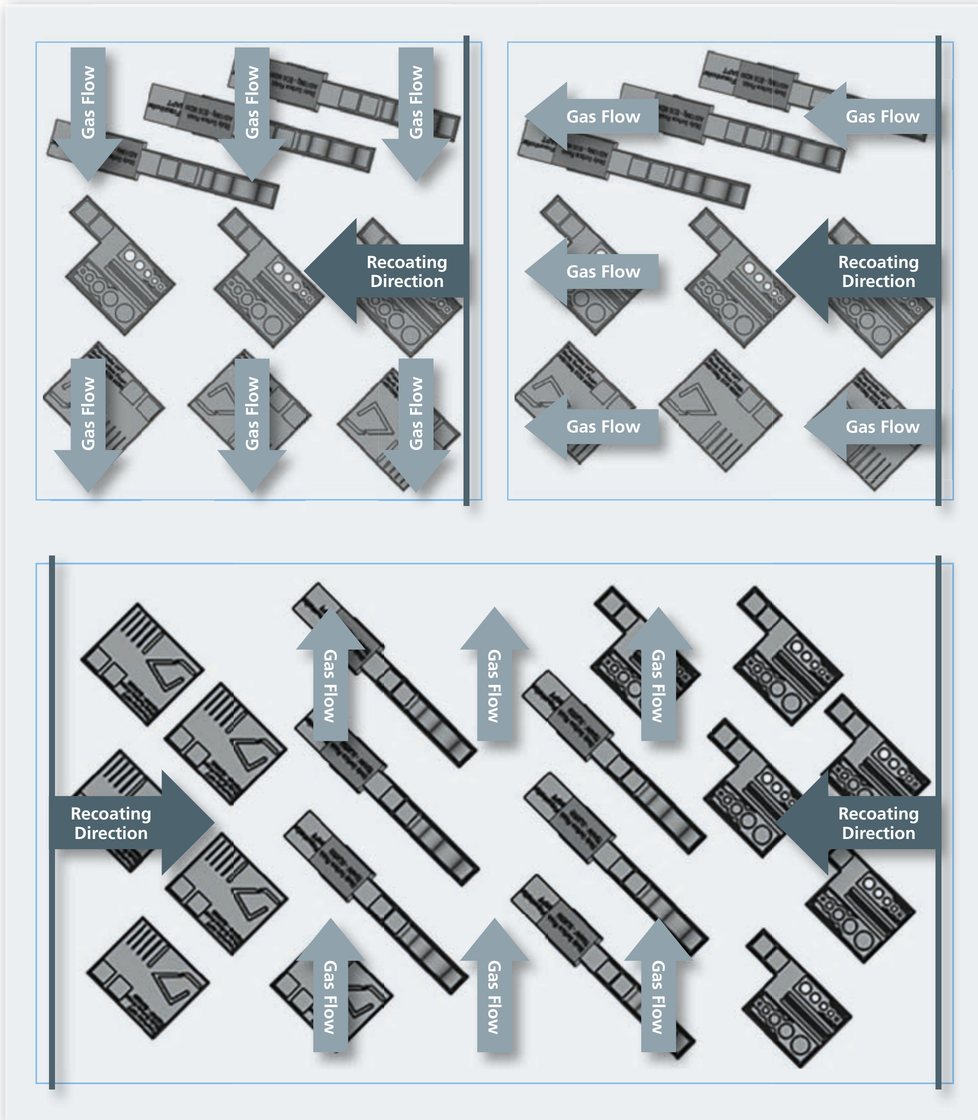


4.3_MANUFACTURING OF SPECIMENS

Each material was printed on a Laser Powder Bed Fusion machine at Fraunhofer IAPT. For the titanium parts, a SLM 500 HL from SLM Solutions Group AG was used. The stainless steel parts were built on a Concept Laser M2 Dual, and the aluminum parts were printed on an EOS M290. For each material parameter-sets developed by Fraunhofer IAPT with a layer thickness of 30 µm were used to achieve a good As-Built surface quality. For all build-jobs the powder recoating was done with a flexible blade, and the process took place under an argon atmosphere. Because of the large extent of the study, it took several build-jobs to print the entire number of necessary test specimens. In total 132 parts were printed, including some backup-parts.

The part orientation on the build-plate was chosen in regard to the direction of the powder recoating and the gas flow of the respective Laser Powder Bed Fusion machine. All parts were positioned with a 45° angle to the recoating direction, except test specimen B in aluminum and stainless steel. Those were positioned with a 15° angle to the recoating direction in order to increase the surface quality of the overhanging areas. For test specimen B material, specific support geometries and parameters were used. All build-jobs with titanium parts then underwent a heat treatment in a vacuum furnace for thermal stress relief.

The printed parts were separated from the build-plates by means of a wire EDM machine. After that, the support structures were manually removed from test specimen B and if necessary the powder adhering to the walls of the small horizontal holes of test specimen A was removed with a small pin. In the last step all the parts were blasted with compressed air to remove any excess powder while maintaining the original As-Built surface.



Arrangement of test specimens on the build-plate of a Laser Powder Bed Fusion machine

Left: AlSi10Mg on EOS M290,
right: 1.4404 on Concept Laser M2 Dual,
bottom: TiAl6V4 on SLM 500 HL

4.4_TESTING METHOD

The testing methods used to benchmark the geometric features of each test specimen are explained below. The exact location of each geometric feature on the test specimen can be found in the material specific result chapter next to each benchmark diagram or chart.

4.4.1_Surface Roughness

The surface roughness is measured optically with the 3D laser scanning confocal microscope VK-8700 (Keyence). The 3D laser scanning confocal microscope generates a three dimensional scan of the surface by scanning the surface pointwise in all three spatial directions. Three measuring points are evaluated on each surface. The measuring point is divided into six segments with a size of 450 x 450 µm. The given surface roughness is the average value of all eighteen segments of the surface. The calculation of the area roughness parameter (Sa) is performed in accordance with DIN EN ISO 25178 using a S-L-surface (S-filter: 2 µm; L-filter: 0.5 mm). A F-operator is chosen according to a plane or curved surface measurement.

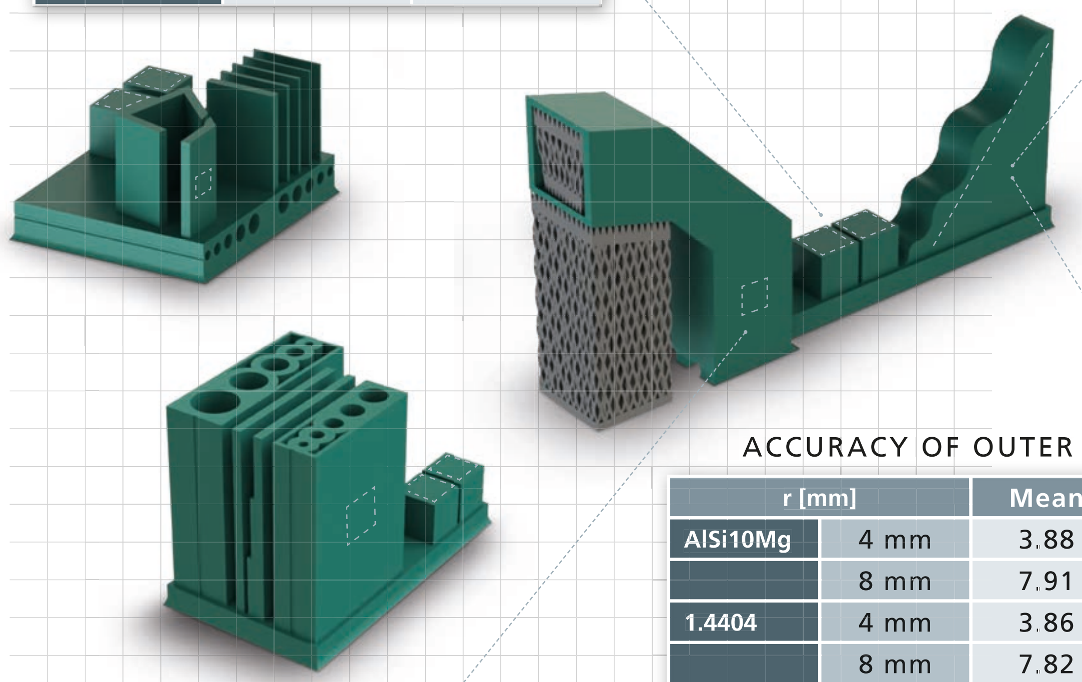
In order to ensure the comparability of the measurement results, the reference surface roughness and dimensional accuracy of the test specimens were measured prior to shipment to the service providers. The following figure shows the mean values and standard deviations from the As-Built condition of the test specimens.

ACCURACY OF INNER RADIUS

r [mm]		Mean	STD
AlSi10Mg	4 mm	3.85	0.081
	8 mm	7.71	0.198
1.4404	4 mm	4.00	0.050
	8 mm	7.77	0.082
TiAl6V4	4 mm	4.04	0.089
	8 mm	7.97	0.121

SURFACE ROUGHNESS: UPPER SURFACE

Sa [µm]	Mean	STD
AlSi10Mg	2.85	0.62
1.4404	7.13	0.95
TiAl6V4	11.95	1.62

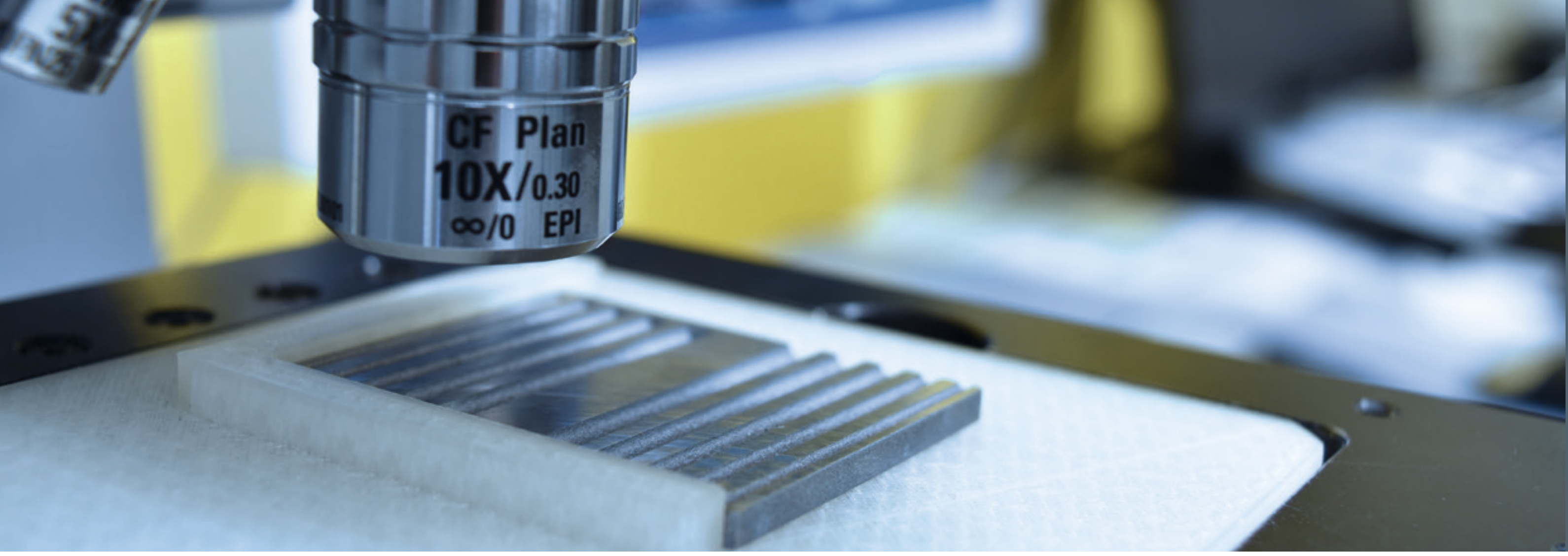


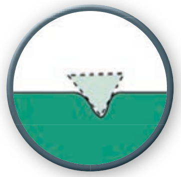
ACCURACY OF OUTER RADIUS

r [mm]		Mean	STD
AlSi10Mg	4 mm	3.88	0.074
	8 mm	7.91	0.132
1.4404	4 mm	3.86	0.105
	8 mm	7.82	0.090
TiAl6V4	4 mm	3.98	0.125
	8 mm	7.81	0.112

SURFACE ROUGHNESS: SIDE SURFACE

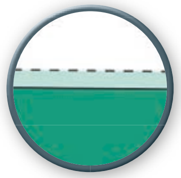
Sa [µm]	Mean	STD
AlSi10Mg	5.18	2.05
1.4404	9.74	1.39
TiAl6V4	15.51	1.45





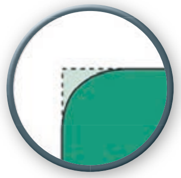
4.4.2_Hardness

The hardness is measured with the Rockwell hardness tester Duramin-150 (Struers). For Ti6Al4V and 1.4404, the Rockwell HRC standard with a 120° diamond spheroconical indenter and a load of 150 kgf (1471N) was used. For the softer AlSi10Mg alloy, Rockwell HRB with a 1.588 mm-diameter steel sphere indenter and a load of 100 kgf (981N) is chosen. The hardness of each specimen is measured at five independent indentation points and the mean of these results is taken as the resulting hardness of the respective specimen. The surfaces are measured as provided from the service providers.



4.4.3_Erosion Rate

The erosion rate is evaluated in two different ways. A visual evaluation based on pictures of the walls is performed to observe damage such as deformation or removal of the walls. The digital microscope VHX-5000 (Keyence) is used to measure the wall thickness at three different locations on the wall. The comparison between the average wall thickness and the reference test specimen quantify the erosion rate.



4.4.4_Edge Rounding

Records of the edges (test specimen A) are taken with the digital microscope VHX-5000 (Keyence). To improve the measurement a focus shift is utilised to generate a depth sharp image of the edges. A measurement of the radius is performed to compare the post processed test specimen with the reference test specimen.

4.4.5_Penetration Depth

Pictures of the holes cut through their centerlines (test specimen A & C) and the lengthways gap (test specimen C) are taken to quantify the penetration depth visually. For holes, a scale ranging stepwise from 100 % to 0 % corresponding to fully processed to no visible processing is used. The gap is rated between 1 and 3 corresponding to fully processed, partly processed and no visible processing. The benchmark criteria is the optical homogeneity of the post processed surface without consideration of the surface smoothing.

4.4.6_Readability

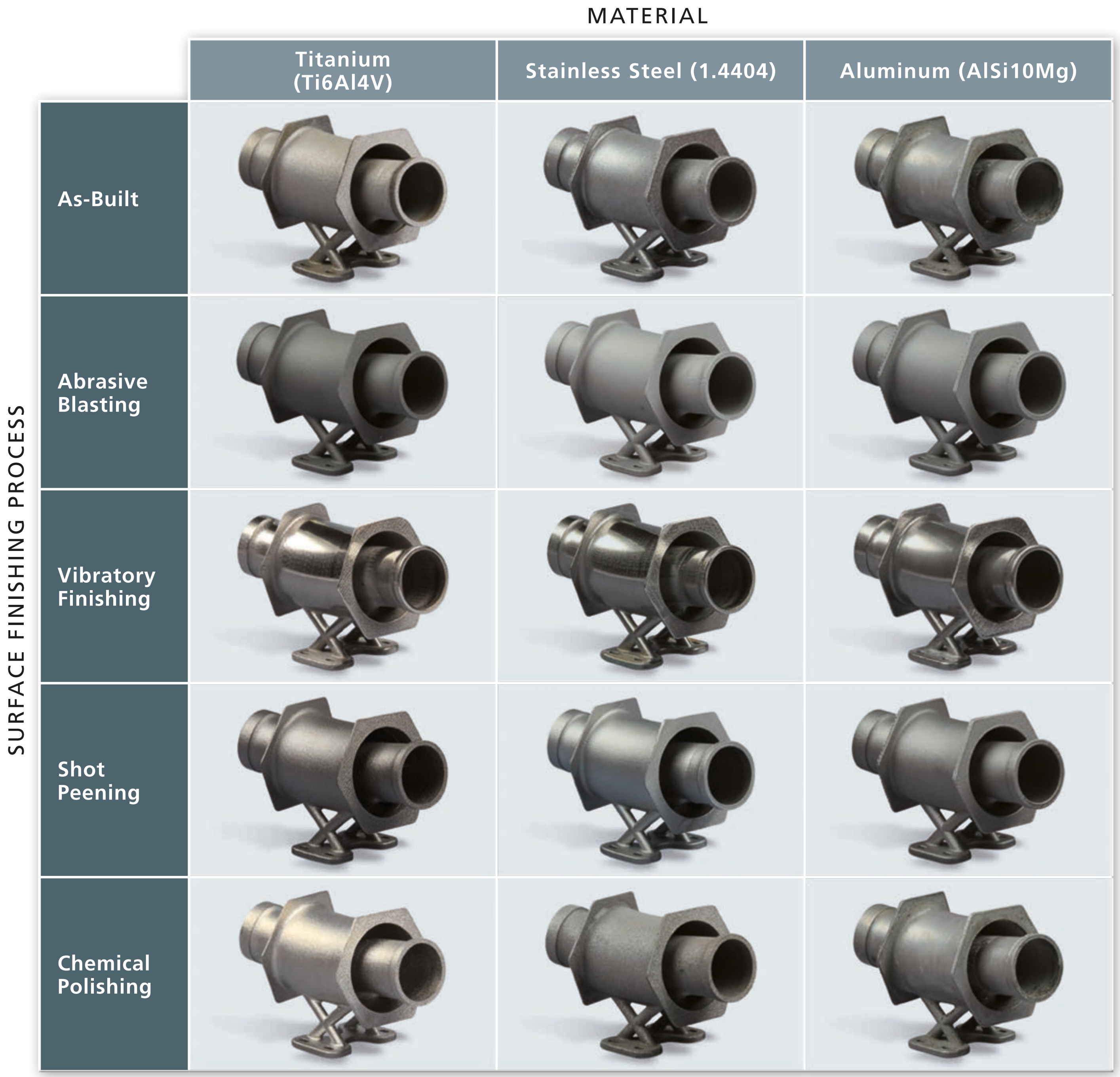
The imprinted and raised lettering (test specimen B) is used to rate the readability after surface finishing. For that purpose, the digital microscope VHX-5000 (Keyence) is used to generate a depth sharp image. The surface finishing method can achieve a better or worse readability compared to the reference specimen.

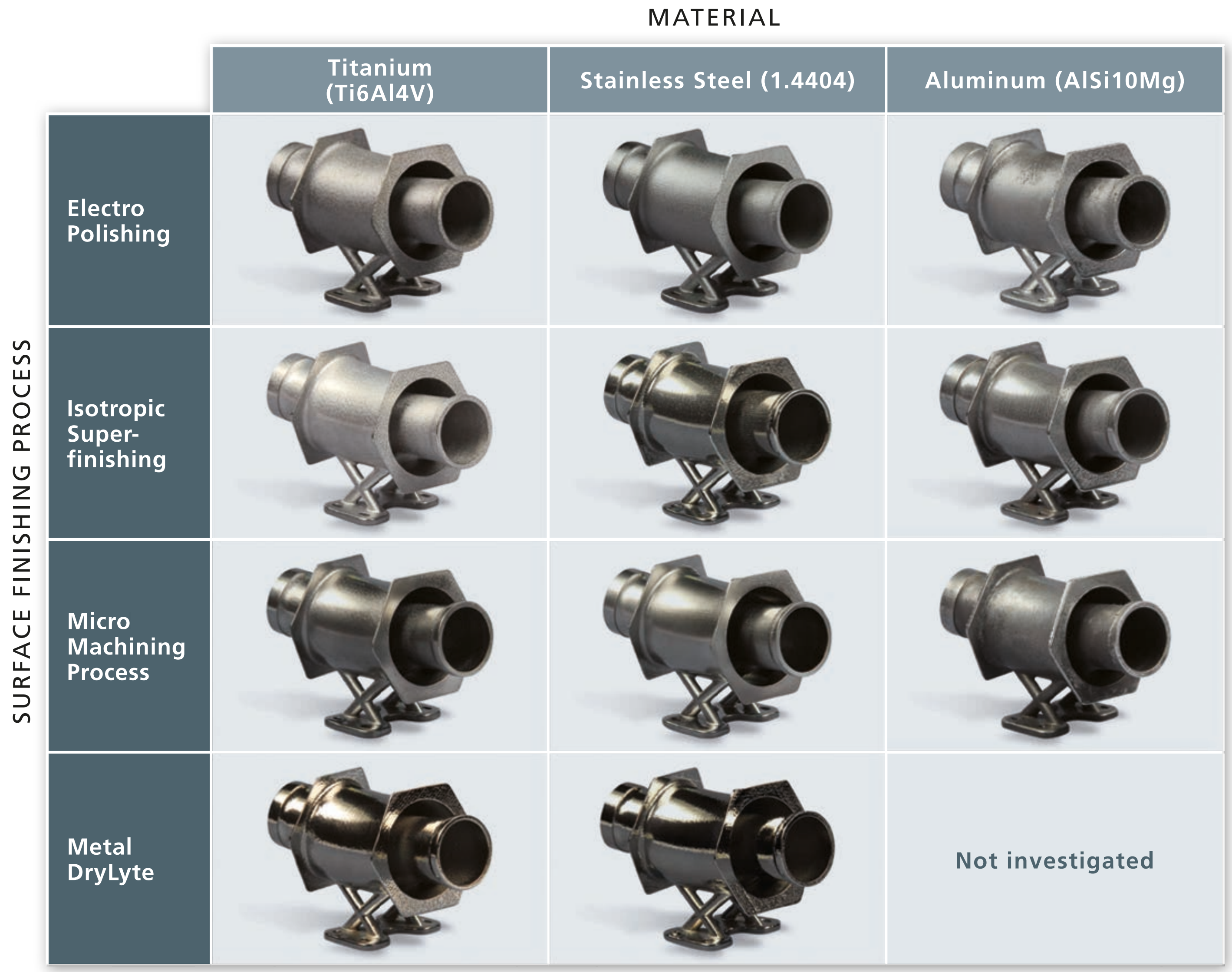
4.4.7_Costs

The costs for the execution of a surface finishing process depend on the following factors: component size, component complexity, component material, lot size and surface requirements. As a fair comparison of costs is difficult, it was decided to do the comparison based on the quotations that were provided by the suppliers for the finishing of the benchmark components. Additionally, the economy of scale as well as main cost drivers are listed.

**Various service providers were contacted to surface finishing the test specimens. The service providers were responsible for choosing the process parameters at their own discretion to find the best compromise with respect to the stated benchmark criteria. Those service providers have been chosen that have experience with finishing of additively manufactured parts and from which the most representative results were expected (e.g. well established system manufacturers or the inventors of the finishing process).*

5_SURFACE FINISHING PROCESSES AT A GLANCE





In the following the operating principle of the investigated surface finishing processes will be explained. The specific parameter settings used for the processes within this study are also named.

Categorization of investigated surface finishing processes

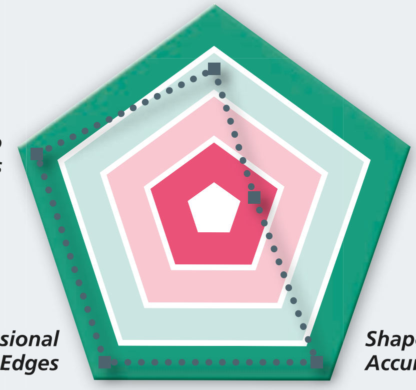
- Machining with undefined cutting edge: Abrasive Blasting, Vibratory Finishing
- Finishing with chemical additives: Isotropic Superfinishing, Micro Machining Process (MMP), Chemical Polishing
- Finishing with electric power: Electro Polishing, Metal DryLyte
- Solidification by plastic deformation: Shot Peening

5.1_ABRASIVE BLASTING

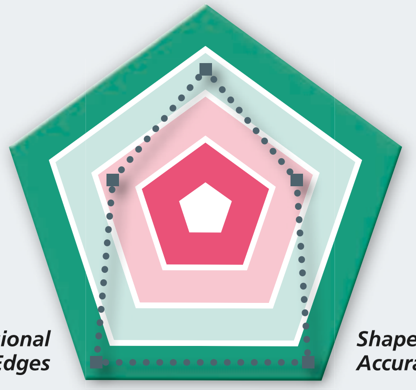
Abrasive Blasting is a surface finishing process that forcibly propels a stream of abrasive material against a surface under high pressure. It belongs to the machining processes with an undefined cutting edge. The most commonly used Abrasive Blasting media is sand but there many other options like corundum. Depending on the blasting media this process aims at smoothing a rough surface, roughing a smooth surface, shaping a surface or removing surface contaminants.

Within this study white fused alumina has been selected as the blasting media with particle diameters in the range between 70 and 150 µm using a blasting nozzle diameter of 5 mm and 1.2 mm (for the slits and holes). Further process-specific information can be found in the annex. Abrasive Blasting is applicable to all additively processable alloys like stainless steels, Inconel, aluminum as well as titanium.

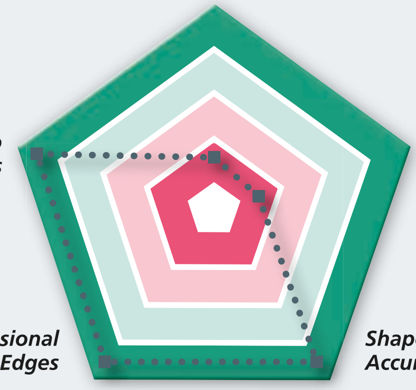
Abrasive Blasting of Stainless Steel



Abrasive Blasting of Titanium



Abrasive Blasting of Aluminum



poor (centre)
moderate
good
excellent (outside)

In the summary chapter, a recommendation for the use of this surface finishing process can be found, which is based on the benchmark results presented here.

6_SURFACE FINISHING OF TITANIUM

Reference: As-Built

SURFACE FINISHING OF TITANIUM

Abrasive Blasting

Vibratory Finishing

Shot Peening

Chemical Polishing

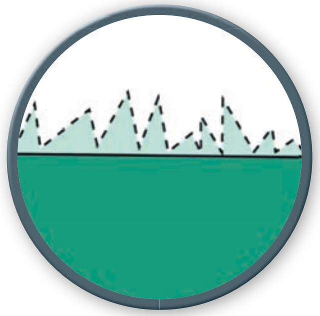
SURFACE FINISHING OF TITANIUM

Electro Polishing

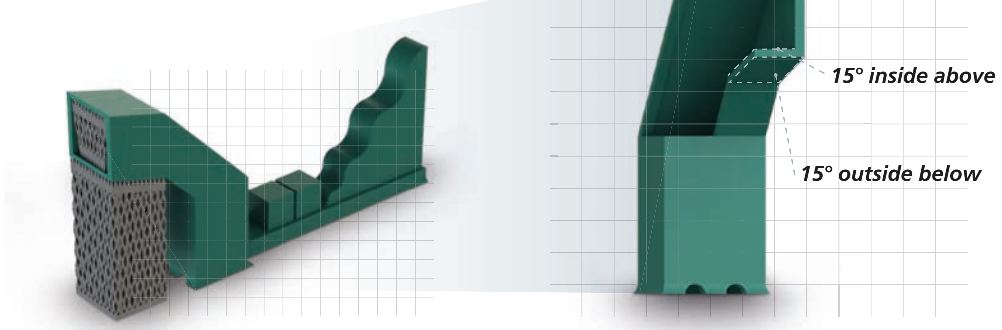
Isotropic Superfinishing

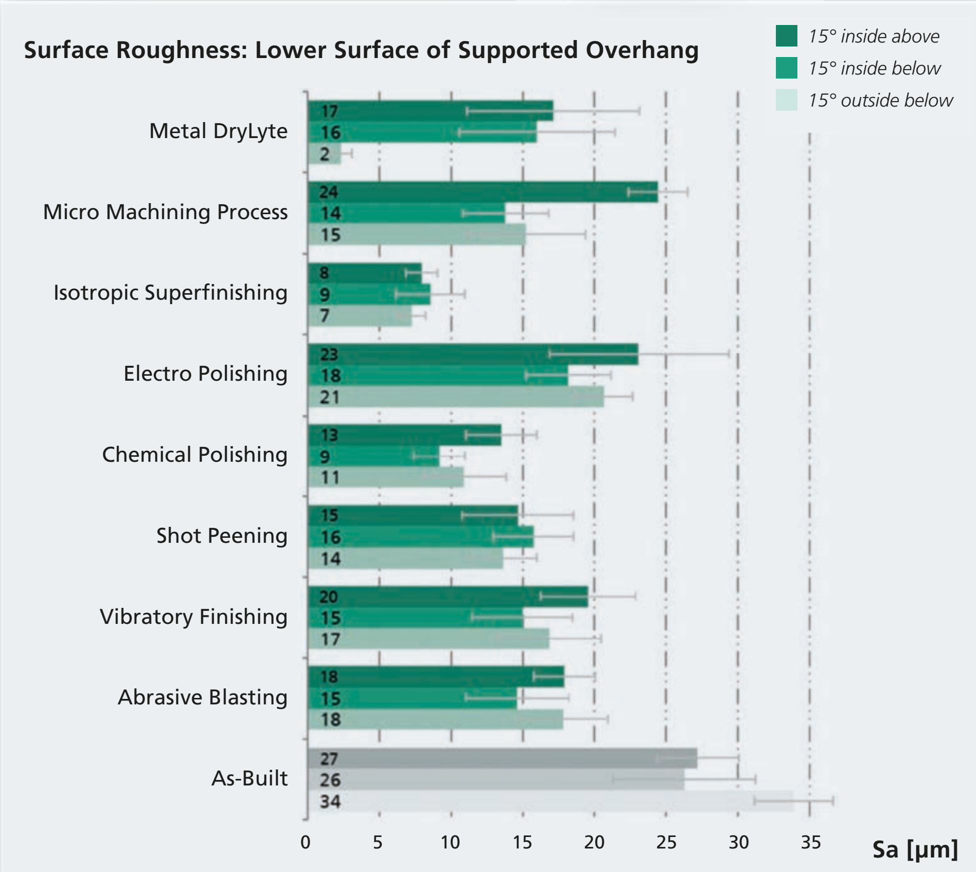
Micro Machining Process

Metal DryLyte

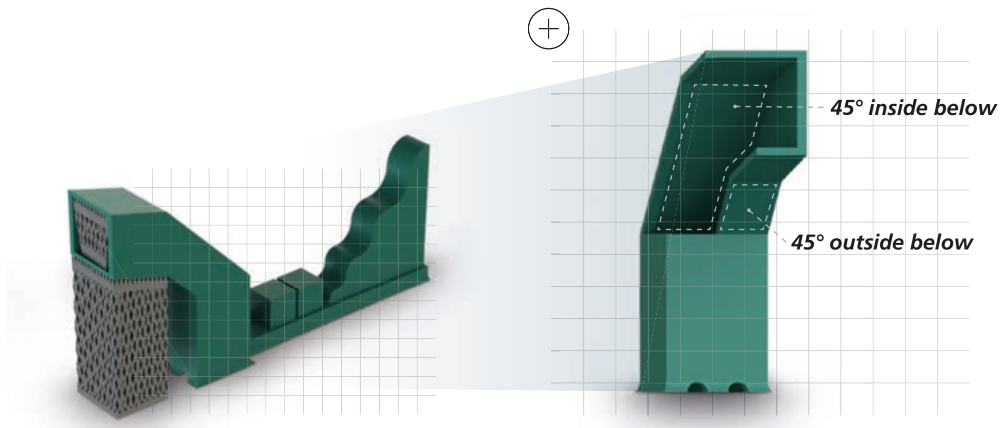


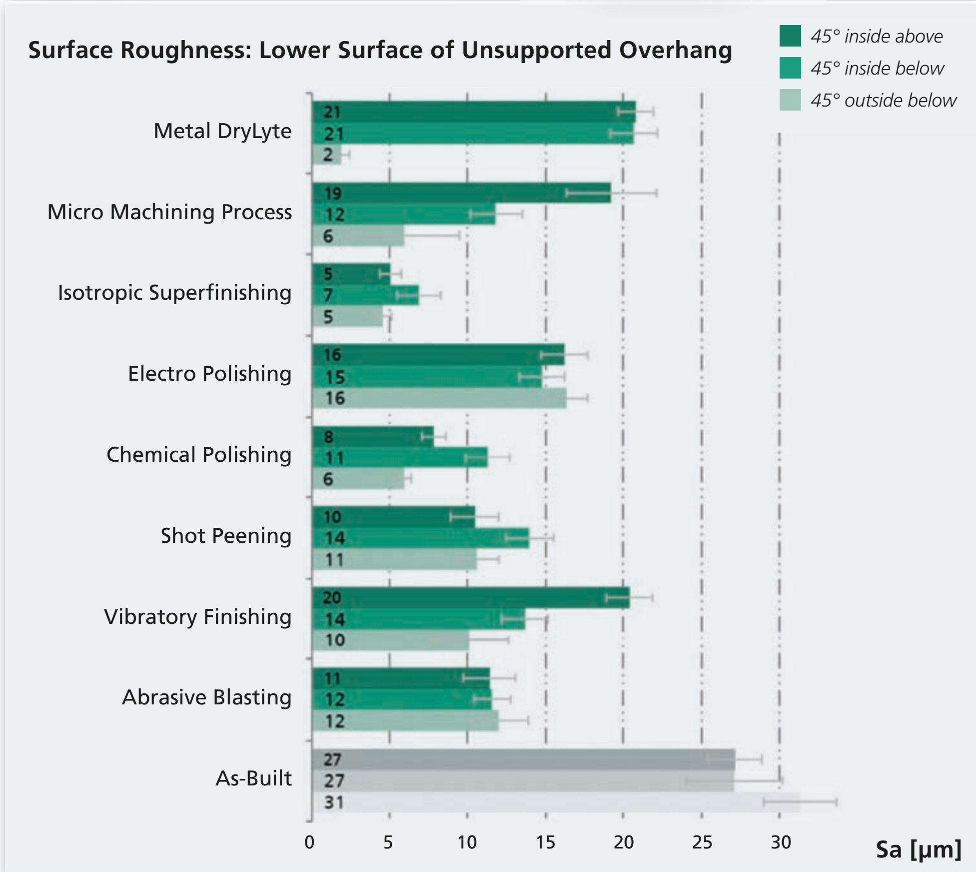
6.1.3_Lower Surface of Overhang

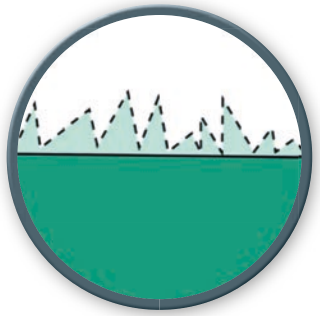




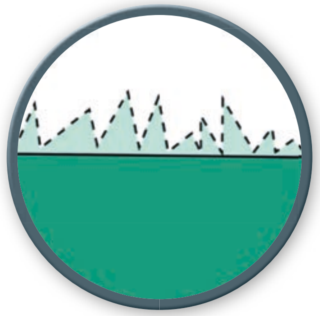
Due to the manual removal of the support structures, there might be a slightly different initial surface quality of the supported areas.



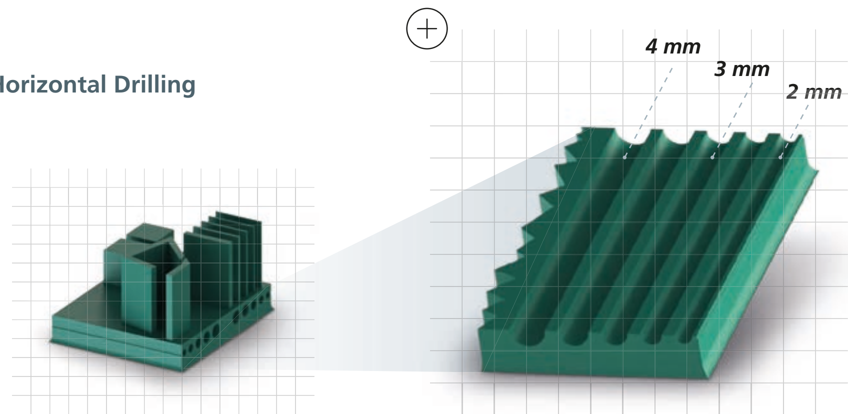


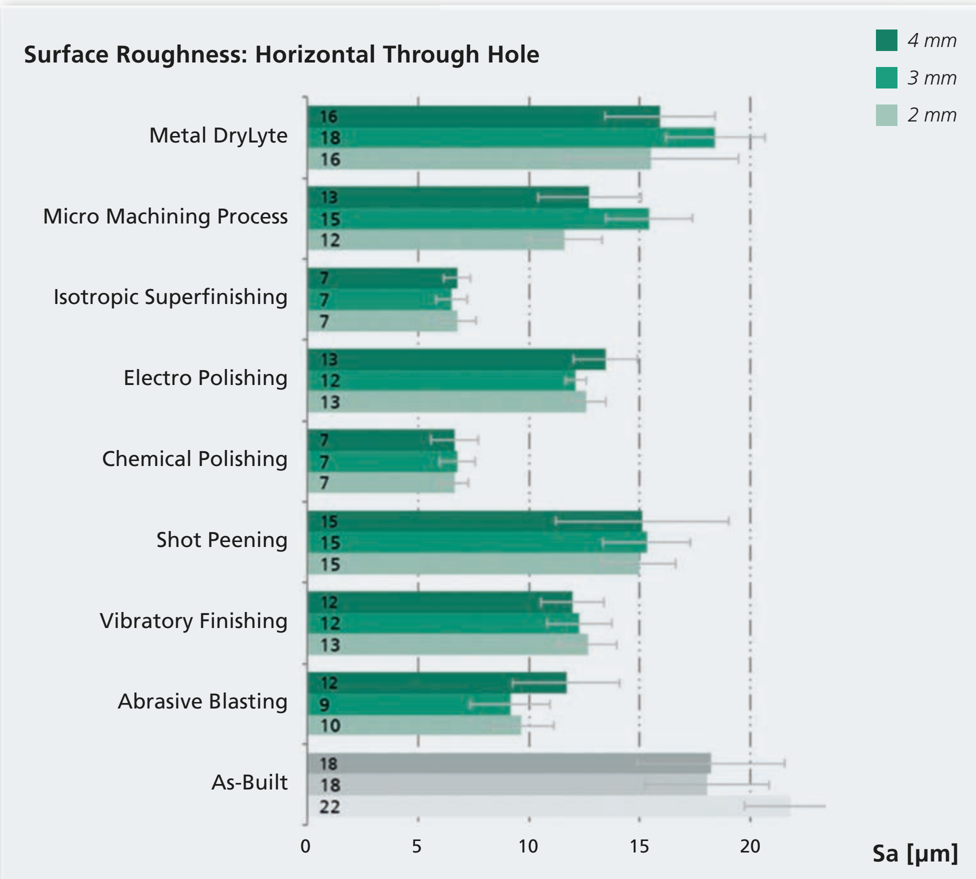


The Electro Polishing process shows a lot of remaining sintered powder particles on the 45° outside below surface.

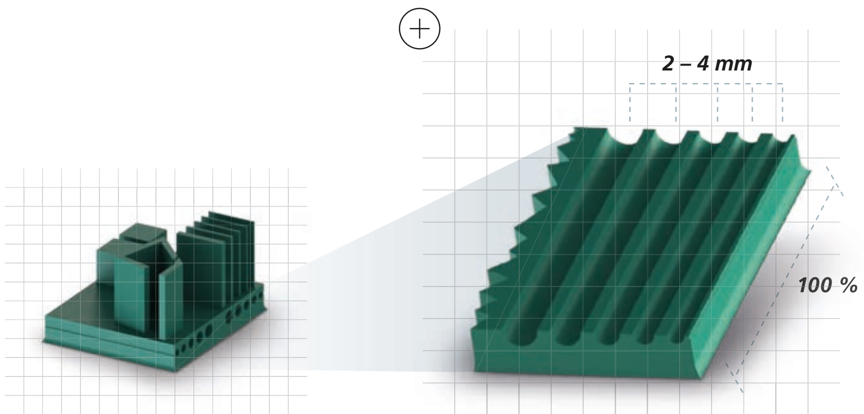


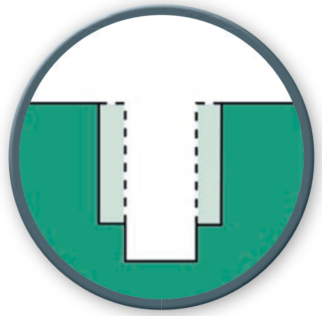
6.1.4_Horizontal Drilling





The surface roughness was measured on the first 5 mm of each hole. For the penetration depth of the processes please refer to the following page.

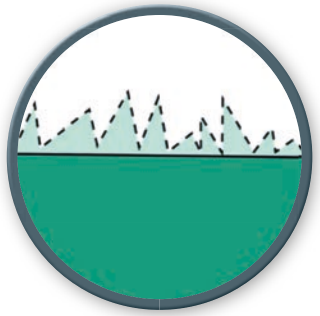


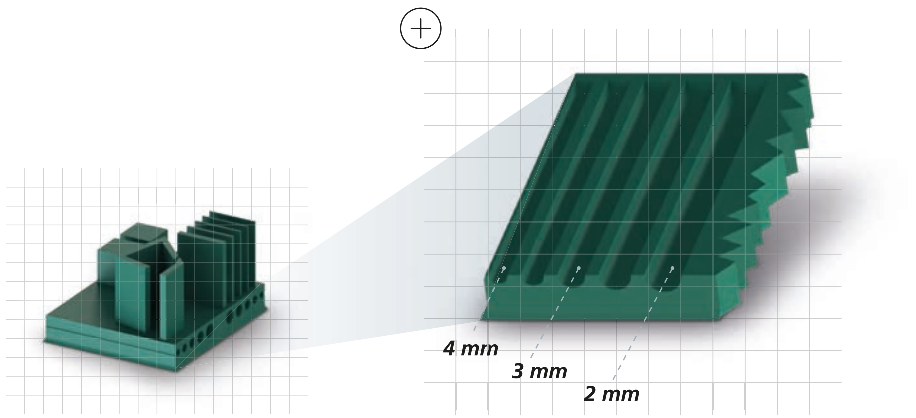


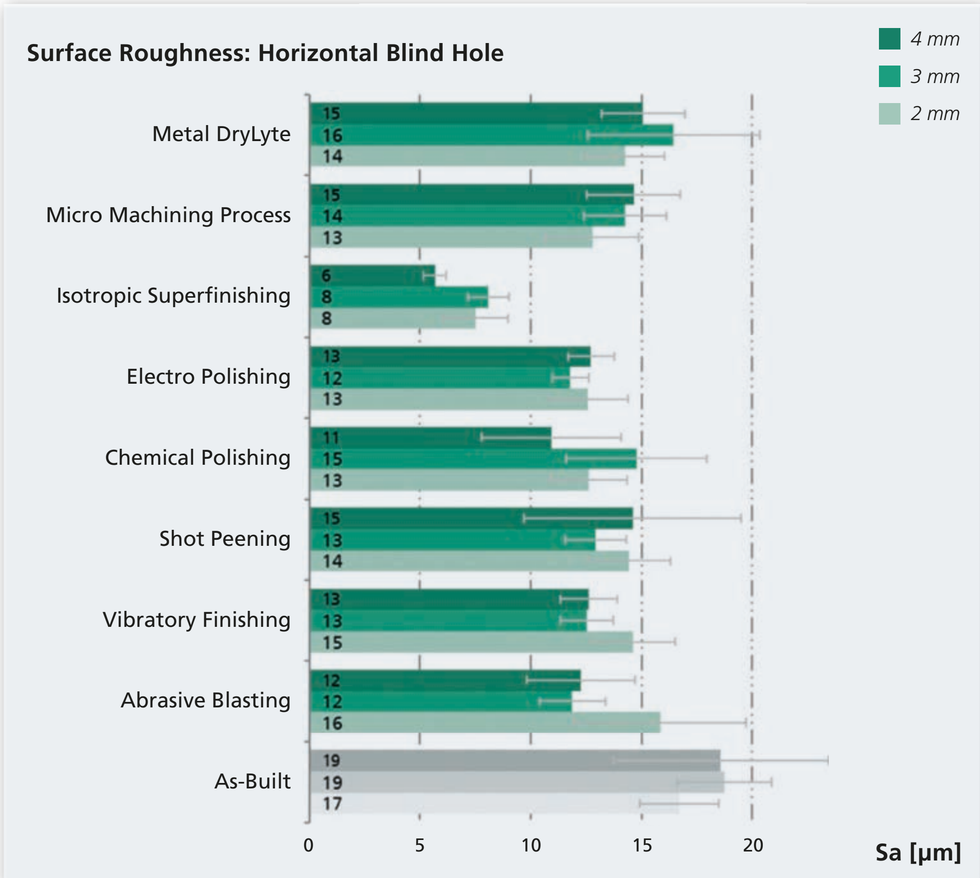
PENETRATION DEPTH: HORIZONTAL THROUGH HOLE

Diameter (mm)	2	2.5	3	3.5	4
Metal DryLyte	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Micro Machining Process	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Isotropic Superfinishing	> 80 %	> 80 %	> 80 %	> 80 %	> 80 %
Electro Polishing	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Chemical Polishing	> 80 %	> 80 %	> 80 %	> 80 %	> 80 %
Shot Peening	> 80 %	> 80 %	> 80 %	> 80 %	> 80 %
Vibratory Finishing	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Abrasive Blasting	> 80 %	> 80 %	> 80 %	> 80 %	> 80 %

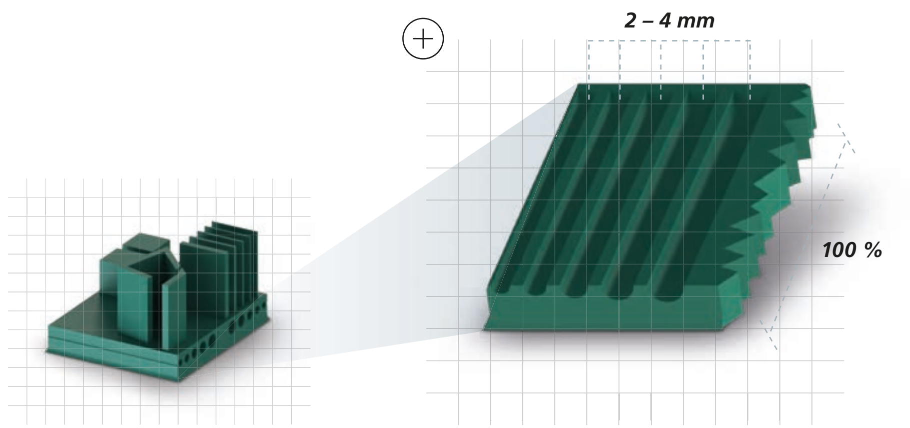
> 80 % of drilling depth
> 60 – 80 % of drilling depth
> 40 – 60 % of drilling depth
20 – 40 % of drilling depth
< 20 % of drilling depth

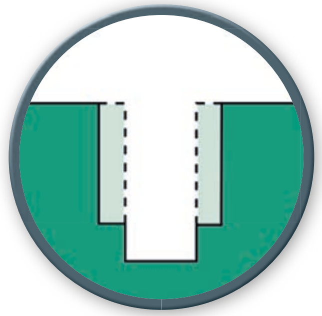






The surface roughness was measured on the first 5 mm of each hole. For the penetration depth of the processes please refer to the following page.





PENETRATION DEPTH: HORIZONTAL BLIND HOLE

Diameter (mm)	2	2.5	3	3.5	4
Metal DryLyte	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Micro Machining Process	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Isotropic Superfinishing	> 80 %	> 80 %	> 80 %	> 80 %	> 80 %
Electro Polishing	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Chemical Polishing	< 20 %	< 20 %	< 20 %	20 – 40 %	20 – 40 %
Shot Peening	> 40 – 60 %	> 60 – 80 %	> 60 – 80 %	> 80 %	> 80 %
Vibratory Finishing	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Abrasive Blasting	< 20 %	< 20 %	< 20 %	20 – 40 %	20 – 40 %

> 80 % of drilling depth
> 60 – 80 % of drilling depth
> 40 – 60 % of drilling depth
20 – 40 % of drilling depth
< 20 % of drilling depth

7_SURFACE FINISHING OF STAINLESS STEEL

Reference: As-Built

SURFACE OVERVIEW FOR STAINLESS STEEL

Abrasive Blasting

Vibratory Finishing

Shot Peening

Chemical Polishing

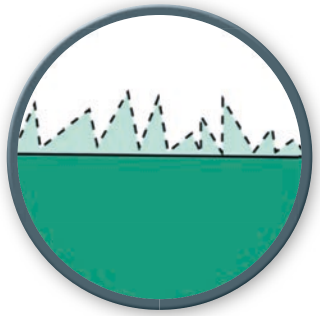
SURFACE OVERVIEW FOR STAINLESS STEEL

Electro Polishing

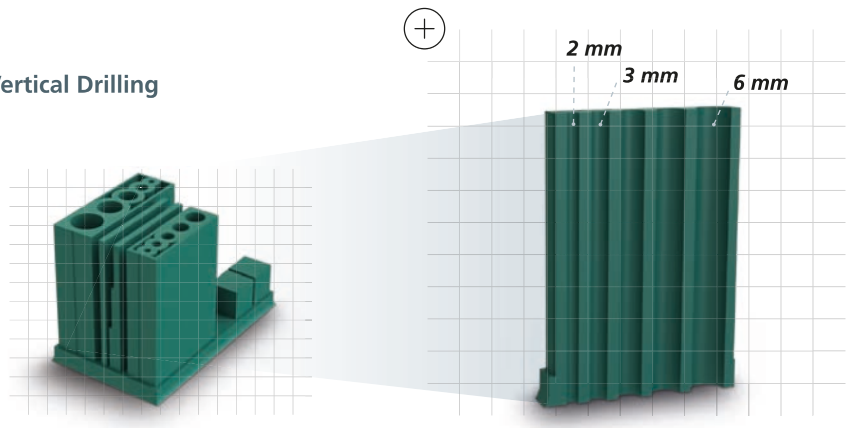
Isotropic Superfinishing

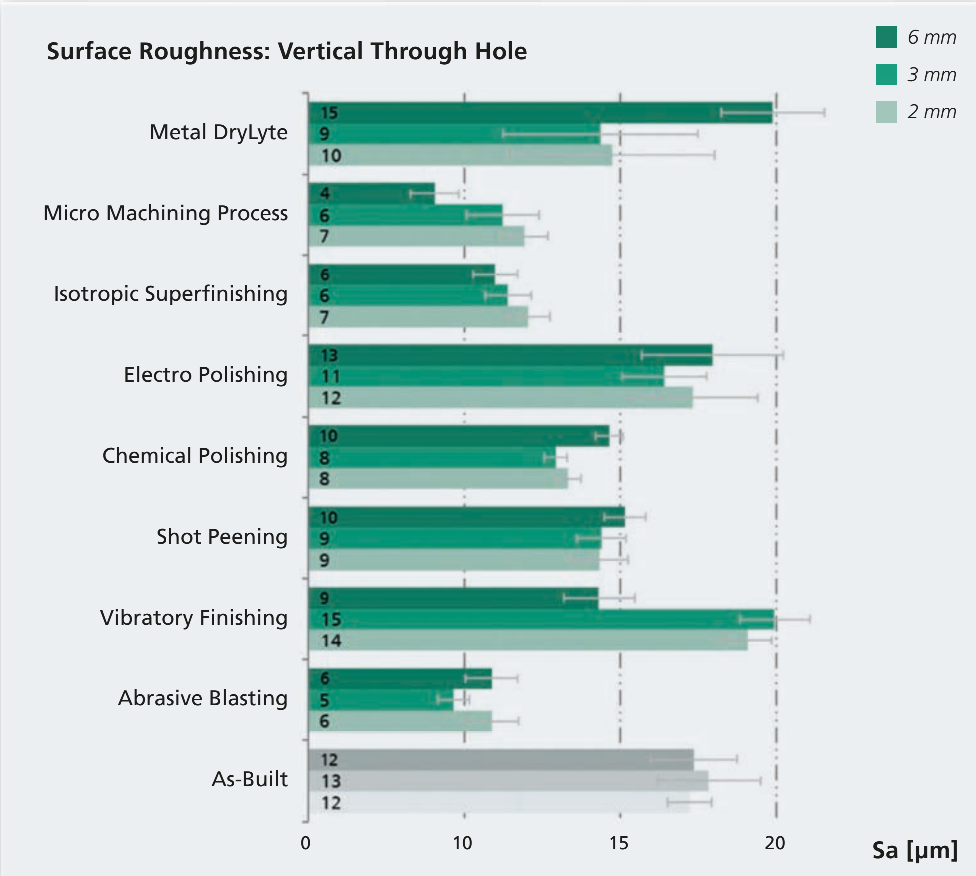
Micro Machining Process

Metal DryLyte



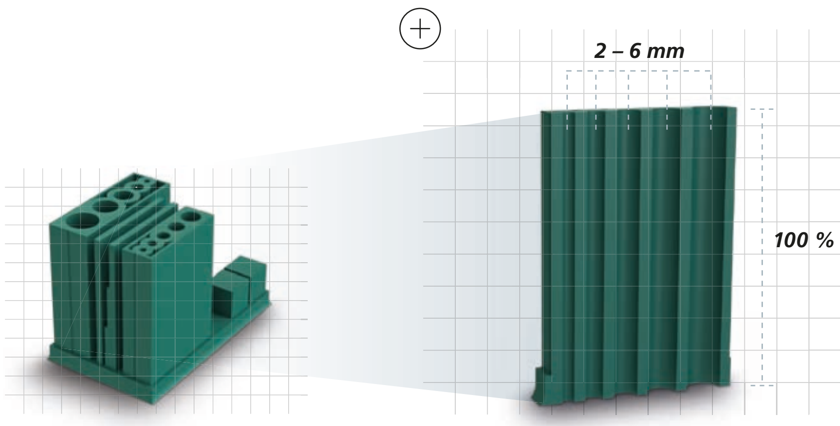
7.1.5_Vertical Drilling

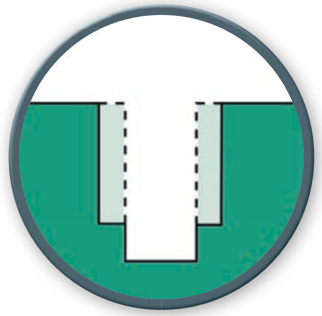




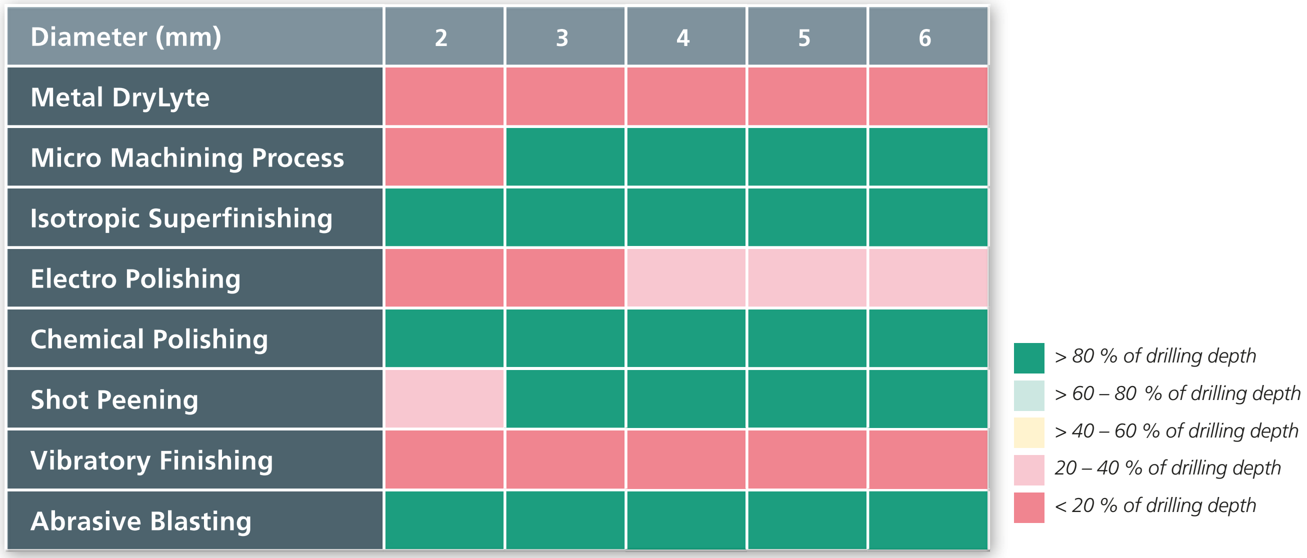
The surface roughness was measured on the first 5 mm of each hole. For the penetration depth of the processes please refer to the following page.

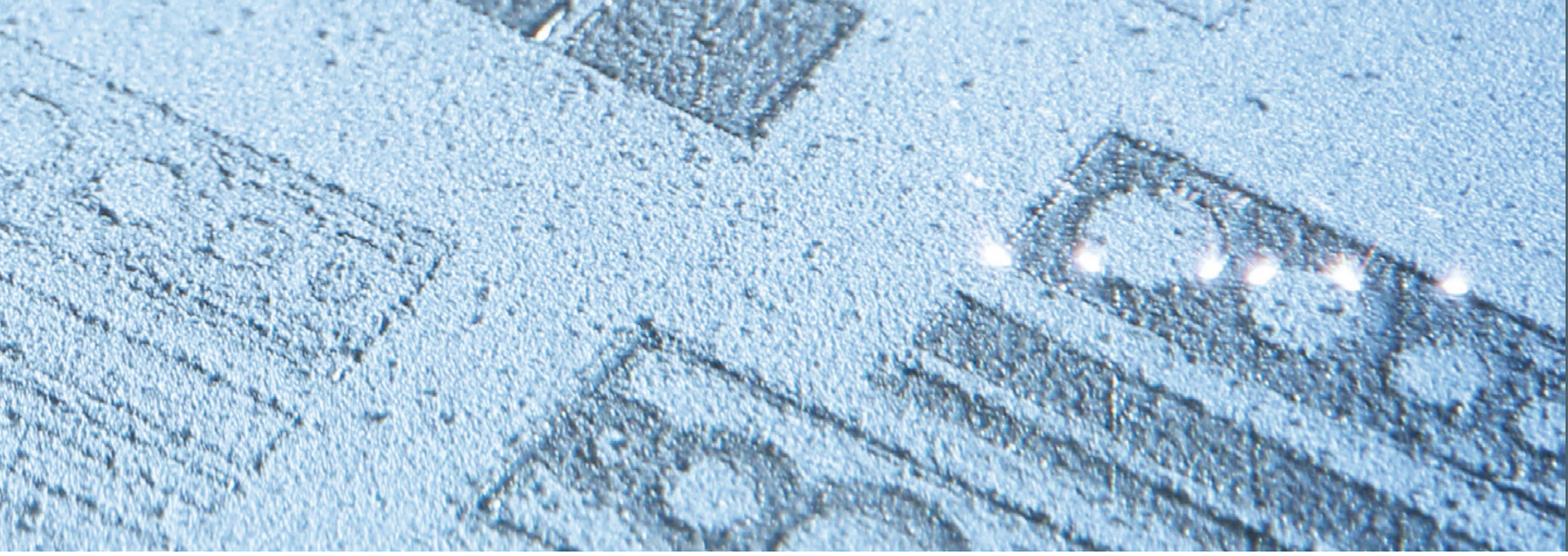
The vertical through hole with a diameter of 6 mm was used for clamping in the Metal DryLyte process and was therefore not finished.

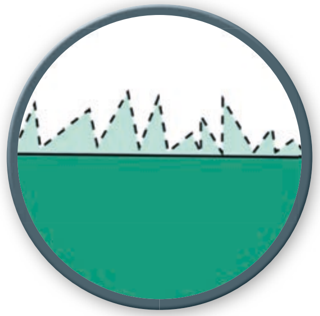


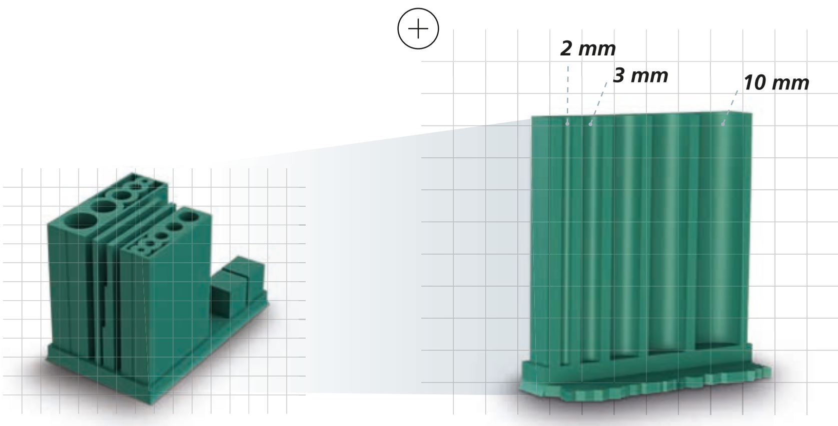


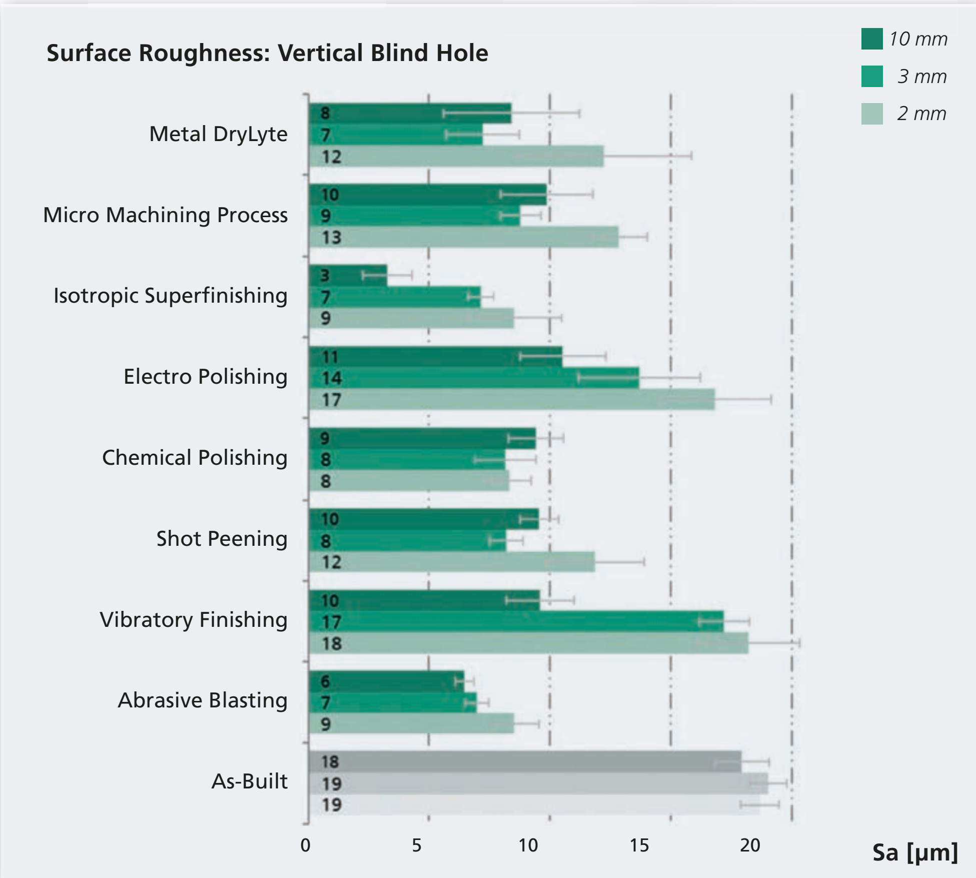
PENETRATION DEPTH: VERTICAL THROUGH HOLE



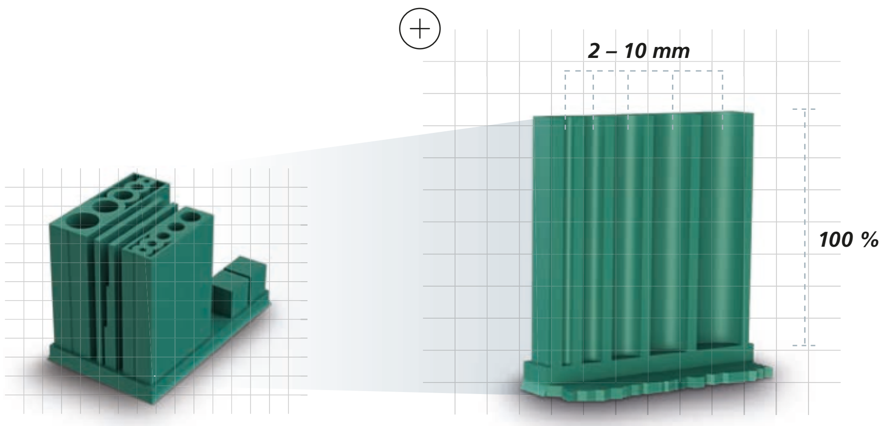


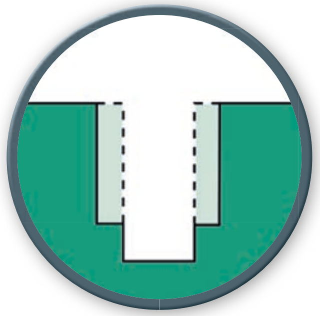






The surface roughness was measured on the first 5 mm of each hole. For the penetration depth of the processes please refer to the following page.

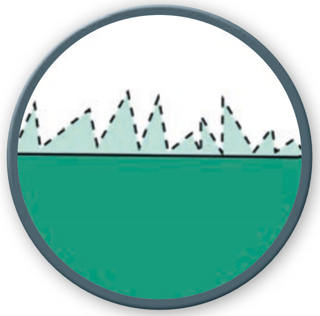




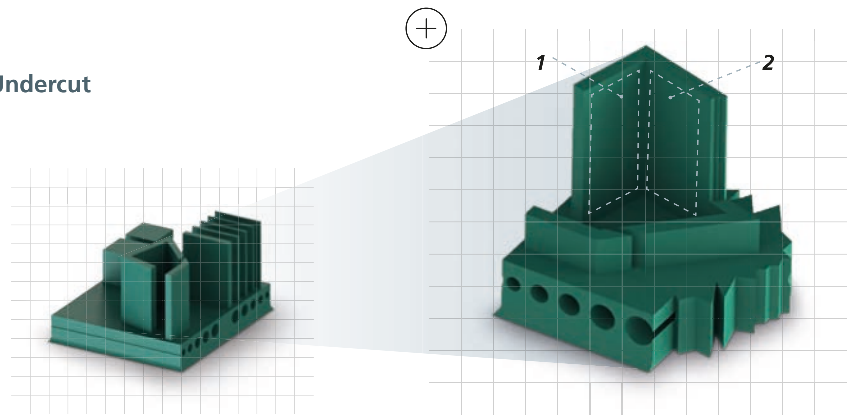
PENETRATION DEPTH: VERTICAL BLIND HOLE

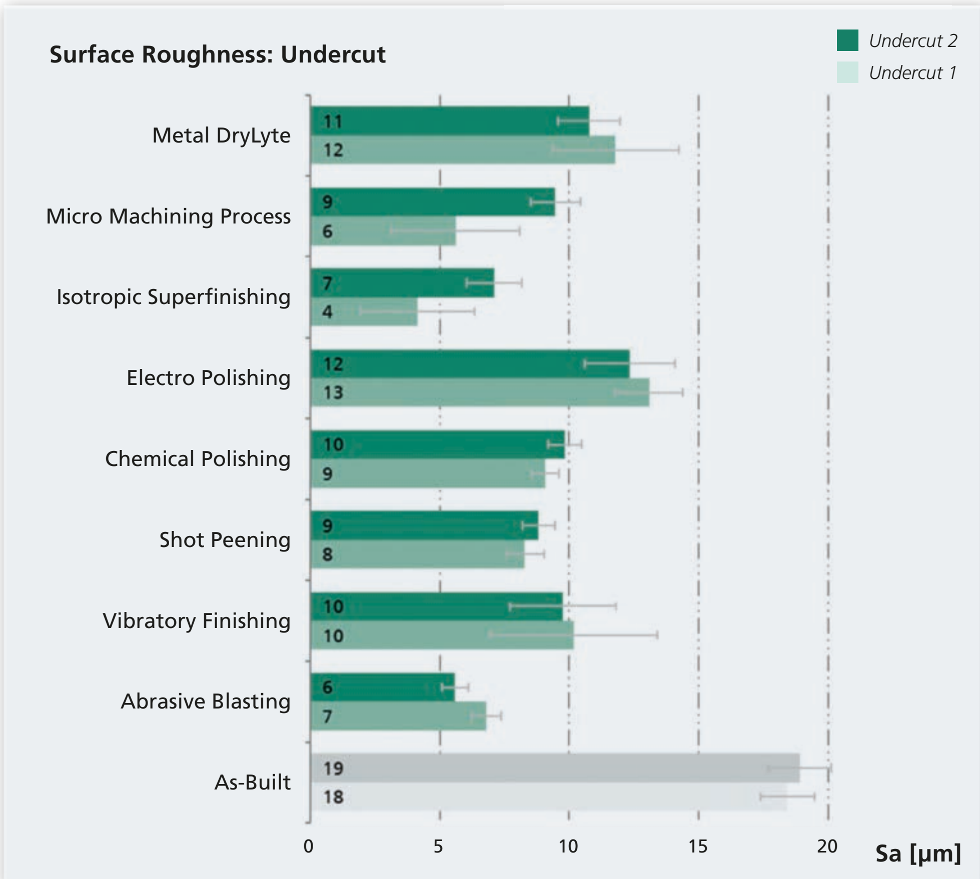
Diameter (mm)	2	3	6	8	10
Metal DryLyte	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Micro Machining Process	< 20 %	> 60 – 80 %	> 60 – 80 %	> 60 – 80 %	> 40 – 60 %
Isotropic Superfinishing	> 80 %	> 80 %	> 80 %	< 20 %	20 – 40 %
Electro Polishing	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Chemical Polishing	< 20 %	< 20 %	< 20 %	20 – 40 %	20 – 40 %
Shot Peening	< 20 %	20 – 40 %	> 40 – 60 %	> 60 – 80 %	> 80 %
Vibratory Finishing	< 20 %	< 20 %	< 20 %	< 20 %	< 20 %
Abrasive Blasting	< 20 %	20 – 40 %	> 40 – 60 %	> 60 – 80 %	> 80 %

> 80 % of drilling depth
> 60 – 80 % of drilling depth
> 40 – 60 % of drilling depth
20 – 40 % of drilling depth
< 20 % of drilling depth



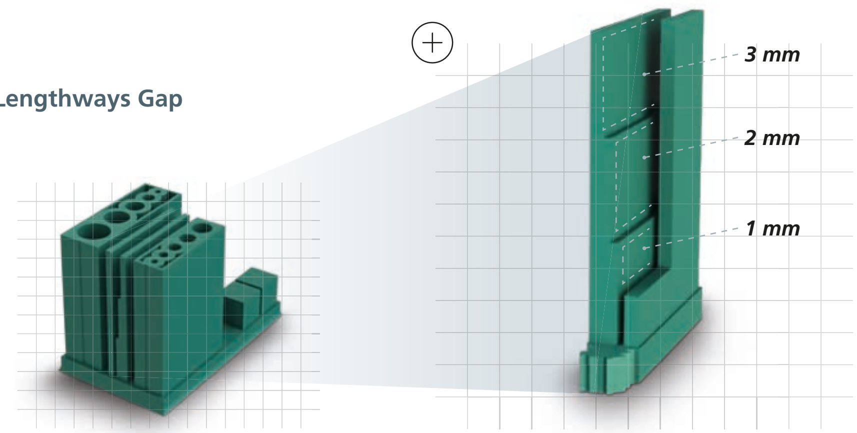
7.1.6_Undercut

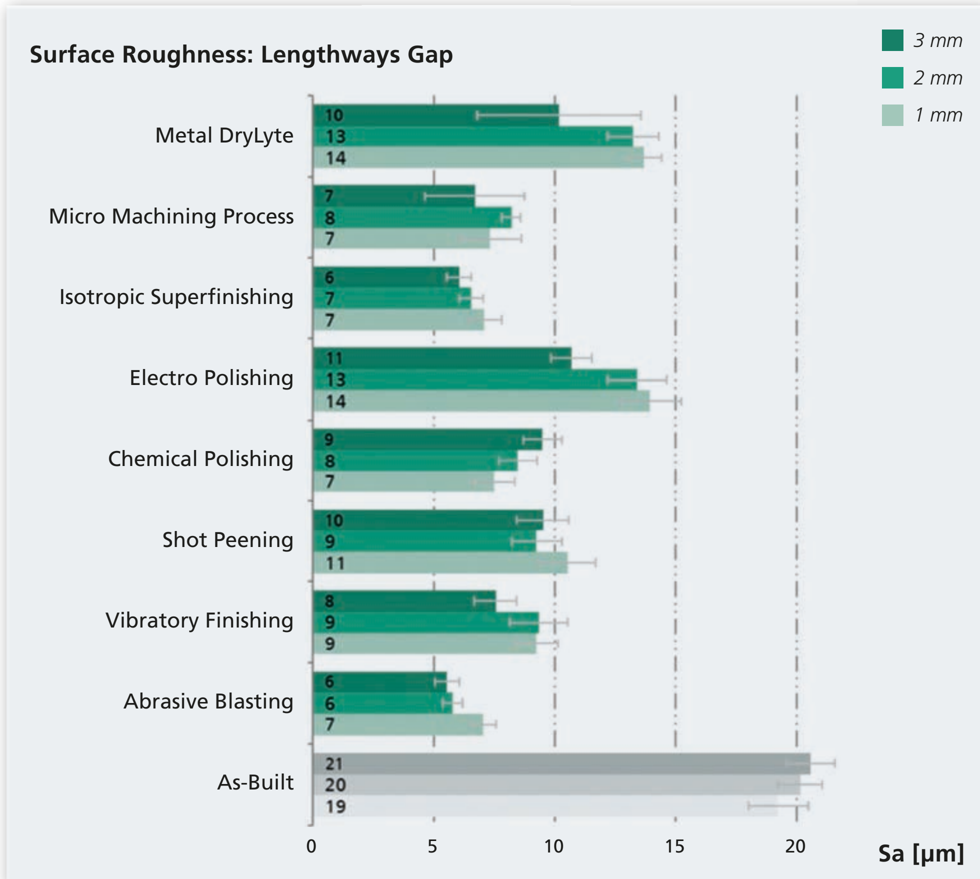


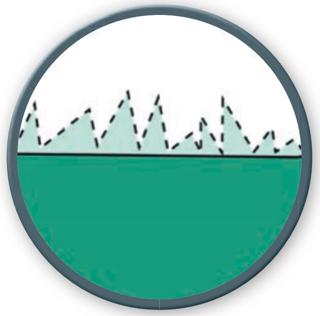


A high standard deviation is caused by a non-uniform processing of the undercut.

7.1.7_Lengthways Gap







The high standard deviation of the Metal DryLyte process is caused by a non-uniform finishing of the lengthways gap.

8_SURFACE FINISHING OF ALUMINUM

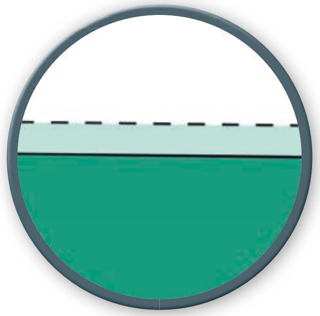
Reference: As-Built

SURFACE OVERVIEW FOR ALUMINUM

Abrasive Blasting	Vibratory Finishing
	
Shot Peening	**Chemical Polishing**
	

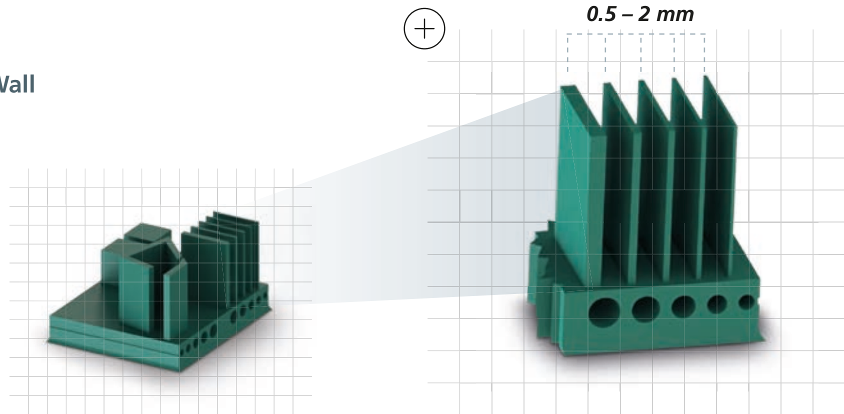
SURFACE OVERVIEW FOR ALUMINUM

Electro Polishing	Isotropic Superfinishing
	
Micro Machining Process	**Metal DryLyte**
	NOT INVESTIGATED



8.3_EROSION RATE

8.3.1_Wall

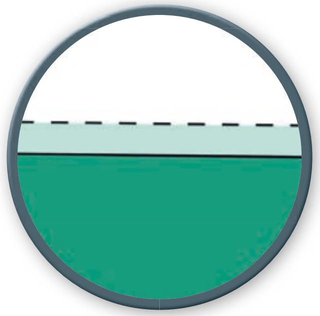


EROSION RATE: WALL

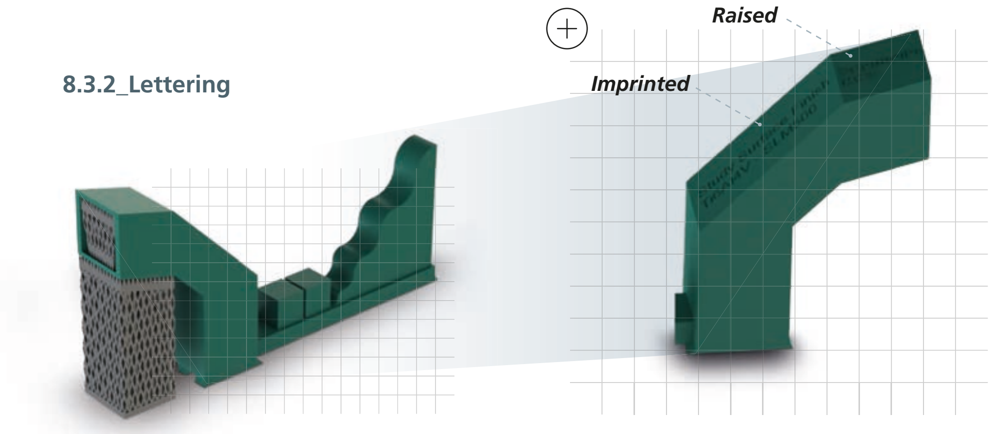
Wall Thickness (mm)	0.5	0.6	0.8	1	2
Micro Machining Process	> 20 – 35 %	5 – 20 %	5 – 20 %	5 – 20 %	5 – 20 %
Isotropic Superfinishing	5 – 20 %	5 – 20 %	5 – 20 %	5 – 20 %	5 – 20 %
Electro Polishing	5 – 20 %	< 5 %	5 – 20 %	5 – 20 %	5 – 20 %
Chemical Polishing	> 35 – 50 %	> 20 – 35 %	> 20 – 35 %	> 20 – 35 %	5 – 20 %
Shot Peening	< 5 %	< 5 %	< 5 %	< 5 %	< 5 %
Vibratory Finishing	5 – 20 %	< 5 %	5 – 20 %	< 5 %	< 5 %
Abrasive Blasting	< 5 %	< 5 %	< 5 %	< 5 %	< 5 %

Thickness Deviation of:

- *< 5 %*
- *5 – 20 %*
- *> 20 – 35 %*
- *> 35 – 50 %*
- *> 50 %*



8.3.2_Lettering

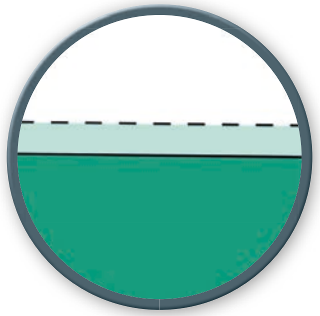


EROSION RATE: LETTERING

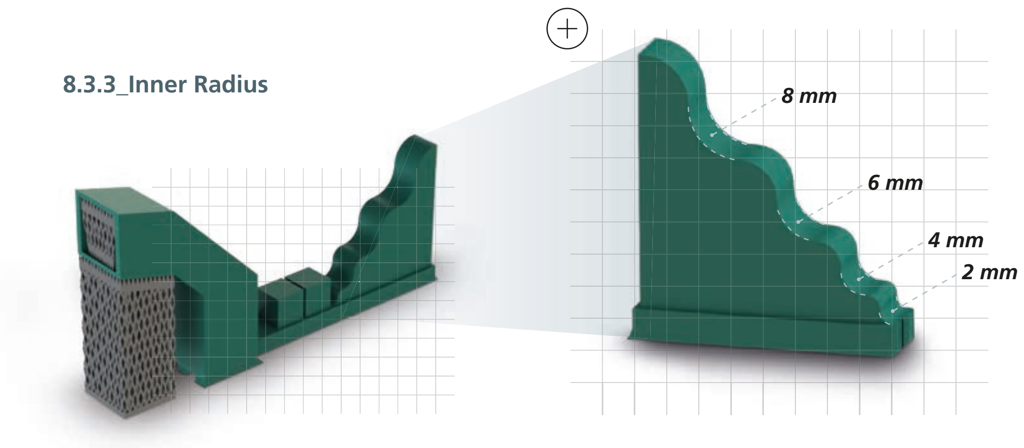
Lettering Type	Imprinted	Raised
Micro Machining Process	Perfectly legible	Not legible
Isotropic Superfinishing	Moderately legible	Not legible
Electro Polishing	Moderately legible	Not legible
Chemical Polishing	Moderately legible	Moderately legible
Shot Peening	Moderately legible	Not legible
Vibratory Finishing	Moderately legible	Moderately legible
Abrasive Blasting	Moderately legible	Not legible

Perfectly legible
Moderately legible
Not legible

MATERIAL



8.3.3_Inner Radius

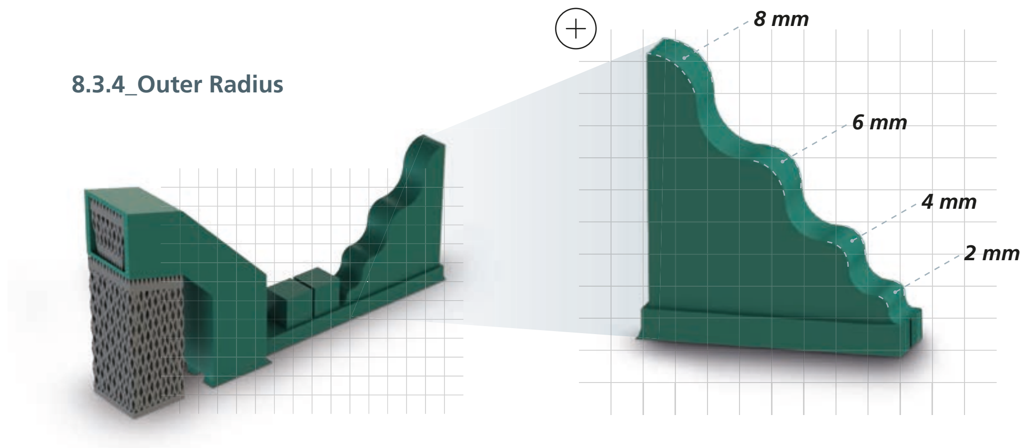


EROSION RATE: INNER RADIUS

Radius (mm)	2	4	6	8
Micro Machining Process	> 10 %	5 – 10 %	< 5 %	< 5 %
Isotropic Superfinishing	> 10 %	< 5 %	< 5 %	< 5 %
Electro Polishing	5 – 10 %	< 5 %	< 5 %	< 5 %
Chemical Polishing	5 – 10 %	< 5 %	< 5 %	< 5 %
Shot Peening	< 5 %	5 – 10 %	< 5 %	< 5 %
Vibratory Finishing	< 5 %	< 5 %	< 5 %	< 5 %
Abrasive Blasting	< 5 %	< 5 %	< 5 %	< 5 %

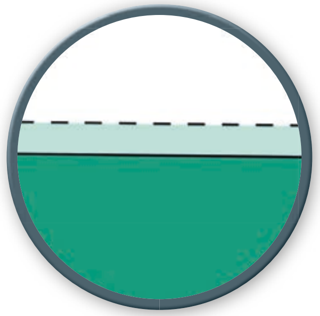
Radius Deviation of:
- *< 5 %*
- *5 – 10 %*
- *> 10 %*

8.3.4_Outer Radius

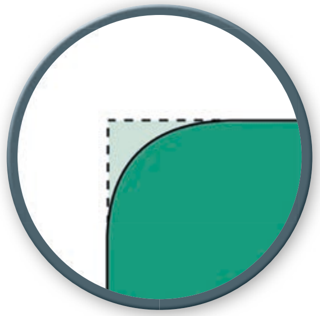


EROSION RATE: OUTER RADIUS

Radius (mm)	2	4	6	8
Micro Machining Process	< 5 %	5 – 10 %	< 5 %	< 5 %
Isotropic Superfinishing	5 – 10 %	< 5 %	< 5 %	5 – 10 %
Electro Polishing	5 – 10 %	< 5 %	< 5 %	5 – 10 %
Chemical Polishing	< 5 %	< 5 %	< 5 %	< 5 %
Shot Peening	< 5 %	< 5 %	< 5 %	< 5 %
Vibratory Finishing	< 5 %	5 – 10 %	< 5 %	< 5 %
Abrasive Blasting	< 5 %	< 5 %	< 5 %	< 5 %

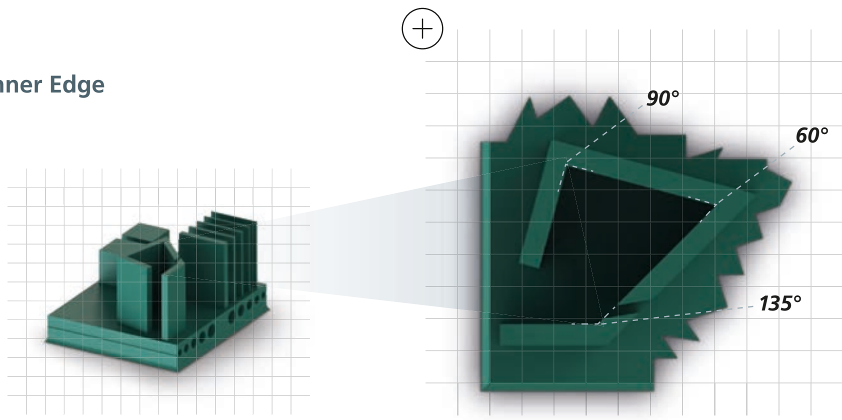


Radius Deviation of:
- *< 5 %*
- *5 – 10 %*
- *> 10 %*

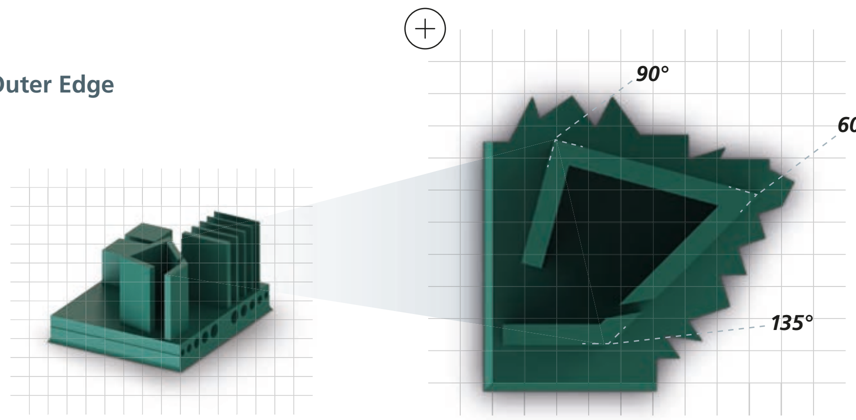


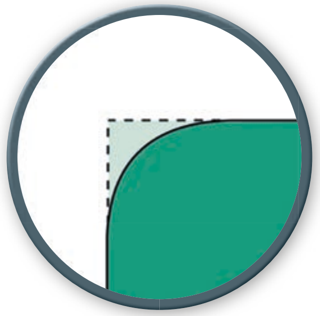
8.4_EDGE ROUNDING

8.4.1_Inner Edge



8.4.2_Outer Edge





EDGE ROUNDING: INNER EDGE

Angle	60°	90°	135°
Micro Machining Process	> 100 %	< 50 %	< 50 %
Isotropic Superfinishing	< 50 %	> 50 – 100 %	> 50 – 100 %
Electro Polishing	< 50 %	> 50 – 100 %	< 50 %
Chemical Polishing	> 100 %	< 50 %	< 50 %
Shot Peening	< 50 %	> 50 – 100 %	< 50 %
Vibratory Finishing	> 50 – 100 %	< 50 %	< 50 %
Abrasive Blasting	< 50 %	> 50 – 100 %	> 50 – 100 %

Edge-Radius Deviation of:
- *< 50 %*
- *> 50 – 100 %*
- *> 100 %*

EDGE ROUNDING: OUTER EDGE

Angle	60°	90°	135°
Micro Machining Process	< 50 %	< 50 %	< 50 %
Isotropic Superfinishing	< 50 %	< 50 %	< 50 %
Electro Polishing	< 50 %	< 50 %	< 50 %
Chemical Polishing	< 50 %	< 50 %	< 50 %
Shot Peening	< 50 %	< 50 %	< 50 %
Vibratory Finishing	> 50 – 100 %	> 50 – 100 %	> 100 %
Abrasive Blasting	< 50 %	< 50 %	< 50 %

Edge-Radius Deviation of:
- *< 50 %*
- *> 50 – 100 %*
- *> 100 %*

Imprint

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